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REPORT

DRI #2608

FINAL REPORT

Contract NAS8-27277

September 1972

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DEVELOPMENT OF EXPLOSIVELY BONDED TZM WIRE REINFORCED COLUMBIAN SHEET COMPOSITES

(NASA-CR-123937) DEVELOPMENT OF EXPLOSIVELY BONDED TZM WIRE REINFORCED COLUMBIAN SHEET COMPOSITES Final Report H.E. Otto, et al (Denver Research Inst.) Sep. 1972 54 p CSCL 13H G3/15

N73-12490

Unclas 16769

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FINAL REPORT

DEVELOPMENT OF EXPLOSIVELY BONDED TZM WIRE REINFORCED COLUMBIAN SHEET COMPOSITES

-by-

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- Prepared for -

National Aeronautics and Space Administration

September 1972

Contract NAS8-27277

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

FOREWORD

The research described herein, which was conducted by the Denver Research Institute, University of Denver, was performed under NASA Contract NAS8-27277 over the period June 1971 to September 1972. The work was done under the management of the NASA Project Manager, Mr. Wayne Morgan, George C. Marshall Space Flight Center.

Henry E. Otto served as Program Director with assistance from Steve H. Carpenter.

ABSTRACT

Methods of producing TZM molybdenum wire reinforced C129Y columbium alloy composites by explosive welding were studied. Layers of TZM molybdenum wire were wound on frames with alternate layers of C129Y columbium alloy foil between the wire layers. The frames held both the wire and foils in place for the explosive bonding process. A goal of 33 volume percent molybdenum wire was achieved for some of the composites.

Variables included wire diameter, foil thickness, wire separation, standoff distance between foils and types and amounts of explosive. The program was divided into two phases: (I) development of basic welding parameters using 5 x 10-inch (127 x 254 mm) composites, and (II) scaleup to 10 x 20-inch composites. Phase I indicated that composites with 0.014-inch (0.36 mm) diameter wire and 0.006-inch (0.15 mm) foil or 0.020-inch (0.51 mm) diameter wire and 0.011-inch (0.28 mm) foil gave the best results. Thicker foils and larger diameter wires had internal flaws.

Problems with wire gathering and incomplete bonding were encountered on scaleup and were not solved during the course of the program.

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I. INTRODUCTION

The purpose of this program was to develop procedures for fabrication of TZM molybdenum wire reinforced columbium alloy composite by explosive bonding. Alternate foil layers of C129Y columbium alloy with interlying layers of wire were to be explosively bonded to give composites with volume percent wire loadings of 33 percent. Several different diameters of wire and thicknesses of foil were used during the course of this program.

The program was divided into two phases: Phase I being to determine the experimental parameters on small 5 x 10-inch (127 x 254 mm) composites, and Phase II being concerned with scaling up to produce 10 x 20-inch (254 x 508 mm) composites. The thickness of the desired composites was 0.07 to 0.120 inches (1.78 to 3.05 mm).

II. EXPERIMENTAL

2.1 Materials

All of the C129Y columbium alloy was supplied by Wah Chang Albany. This material was supplied in two lots with different ingot analyses for both lots and within a particular lot. Nominal composition of the C129Y alloy and the average ingot analyses supplied by Wah Chang is presented in Table 1. The 0.006 and 0.011-inch (0.15 and 0.28 mm) foil used in Phase I was from Ingot 572057. All of the 0.017-inch (4.3 mm) foil used in Phase I and II was from Ingot 572053 as was a portion of the 0.011-inch foil used in Phase II. All of the 0.008-inch (0.19 mm) foil used in Phase II was from Ingot 572053. A portion of the 0.011-inch foil used in Phase II was from Ingot 572068. For Phase I the materials were shipped over a period of 2 months and for Phase II over a period of 1-1/2 months. Wah Chang did experience difficulty in rolling the thinner foils and the 0.006-inch stock was remelted once before the foil was shipped.

None of the 0.006,0.008, or 0.011-inch foil was flat but appeared to have been rolled on a mill without enough crown to actually give a flat sheet. Measurement indicated that on the 0.006-inch foil the center thickness was 0.006 inches whereas thickness at the edge was 0.0057 to 0.0058 inches. The same variation was noted for the 8 and 11 mil. foils. The degree of flatness did not have too great an effect in Phase I but Phase II with the larger welds problems were encountered in obtaining a constant standoff between the foil layers.

All of the TZM molybdenum wire used in Phase I was supplied by NASA. This wire was manufactured by Wah Chang-Huntsville. Both the 0.010 and 0.014-inch (0.25 and 0.28 mm) wire were coiled while the 0.02 and 0.032-inch (0.5 and 0.8 mm) wire came in 6-foot (1.8 meter) straightened lengths. The 0.020-inch wire used in Phase II was coiled and was purchased directly from Wah Chang-Huntsville. All of the wire required tensioning to keep it straight regardless of whether it was supplied as "straightened" wire or not. In the small scale welds with the

Table 1

Nominal and Ingot Analyses

of C129Y Columbium Alloy

Element	Nominal	Ingot 572057	Ingot 572053	Ignot 572068
	Percent Each Element			
Tungsten	9-11	10.1	9.35	9.2
Hafnium	9-11	10.2	9.6	9.85
Tantalum	0.5	0.32	0.36	0.33
Yttrium	0.05-0.3	0.1	0.1	0.14
Zirconium	0.5	0.25	0.23	0.16
Carbon	150 ppm	70 ppm	30 ppm	55 ppm
Oxygen	225 ppm	120 ppm	135 ppm	130 ppm
Nitrogen	100 ppm	45 ppm	30 ppm	27 ppm
Hydrogen	15 ppm	2.6 ppm	4.1 ppm	7 ppm
Columbium	Bal	Bal	Bal	Bal
All Others	> 3000 ppm	--	456 ppm	360 ppm

straightened 0.020 and 0.032 inch wire the degree of straightness was not too much of a problem as tensioning was easier. On the longer welds in Phase II straightness was a major problem which was the reason for using coiled wire instead of a straightened shorter length stock.

There was a variation in the two lots of 0.014-inch diameter wire with the first lot being easy to wind whereas the second lot, which was not used until Phase II, cracked and failed on bending. This lot was reprocessed by

Wah Chang by giving it an additional anneal at 1000°C for one hour.

The cracking and fracturing problem was alleviated to some extent but caution had to be exercised during winding to prevent double bending, which invariably caused cracking.

Explosives used on this program were procurred from Du Pont. The various explosives used and their detonation velocities were (1) Detasheet, 7200 m/sec, (2) 40% Red Cross Extra Dynamite, 2800-3500 m/sec, and (3) 40% Free Running Dynamite, 1200 m/sec. These explosives were used as the main welding charge. In addition Du Pont El 502 line wave detonators were used to obtain a line wave detonation front with all tests. For those tests with charges on both sides of the weld C-2. Detasheet strips were used to connect the line wave detonators. All charges were electrically detonated with number 6 blasting caps.

2.2 Development of Procedures to Fabricate 5 x 10-inch TZM Molybdenum Reinforced C129Y Columbium Alloy Composites

Procedures developed by other investigators for the production of wire reinforced composites varied widely. Layup procedures include wrapping the wire around the metal foils[5], laying the wire on the foil and taping the ends[3], winding the wire with a lathe on a mandrel[4,7], slotting the foil and laying the wire in the slots[10], and winding the wire on a mandrel with multiple strands through spacer slots[11]. For explosive welding of composites the wires should be straight and parallel with even spacing between them for welding. To achieve a high volume percent loading of reinforcing filament, the wires should be staggered for each layer to minimize wire flattening.

For this program mandrels or harps were used for layup of the wires. These harps were constructed of mild steel. In using the harps, the frame served two purposes: (1) to hold the wire in position, and (2) to act as spall rails on the sides to allow welding to the edge without fracture. Sketches of the basic arrangement are shown in Figures 1 and 2.

In the initial stages of the program stainless steel foil and tungsten wire was used to determine explosive welding parameters as well as blasting

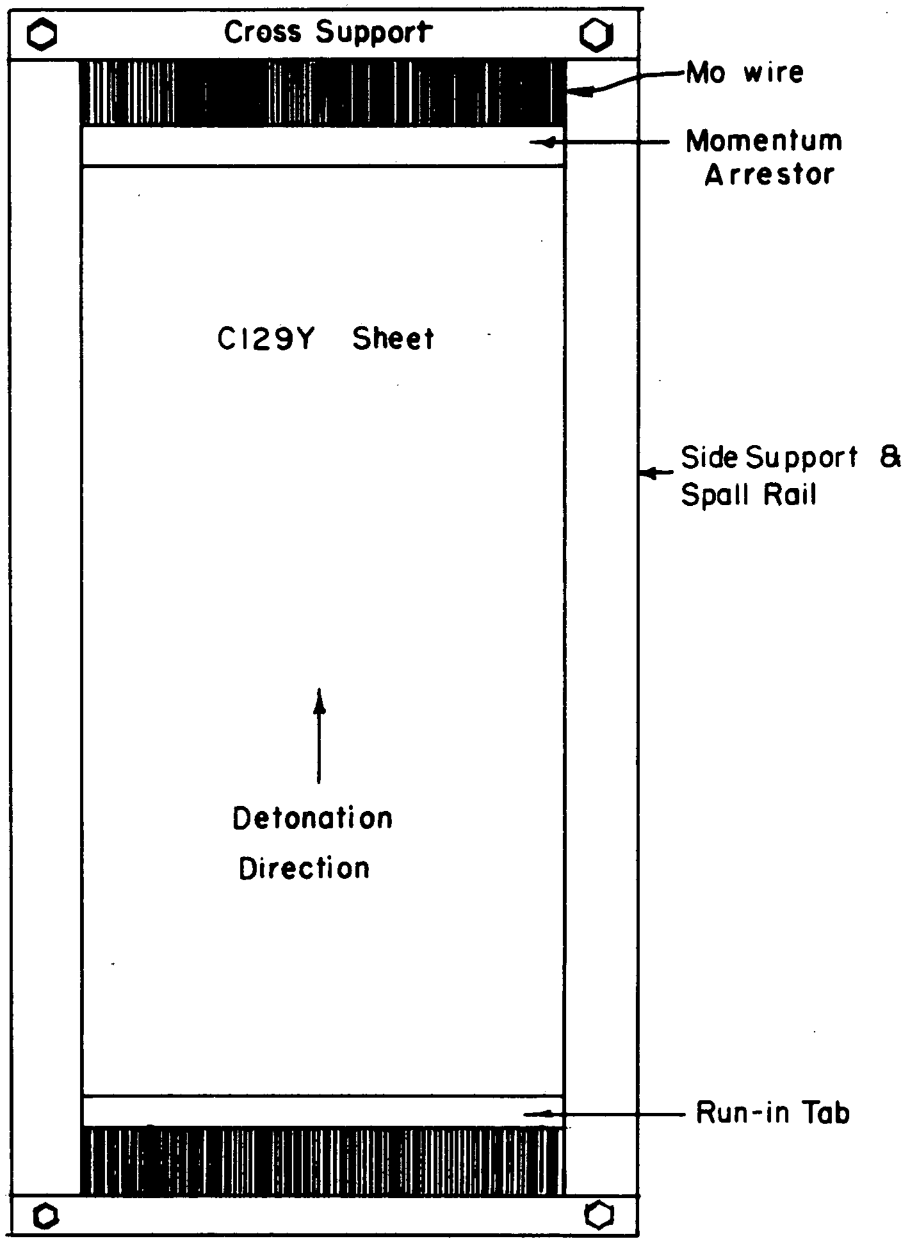


Figure 1. Sketch of Top View of Explosive Welding Arrangement.

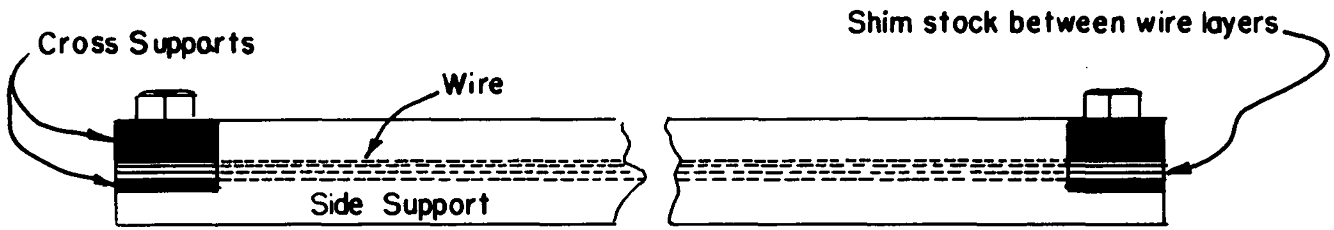


Figure 2. Sketch of Side View of Welding Assembly Without Buffer System.

procedures. Of interest were buffer systems to allow the foils to deform around the wire. In the first series of tests a 1/16-inch sheet of neoprene rubber was glued to the top foil layers. Stainless steel foil measuring 0.010 inches (0.254 mm) in thickness was used with two layers of 0.010-inch diameter tungsten wire. The wire was wound around the end frames and glued with Duco cement. The winding interval was 0.015 inches (0.38 mm) and the standoff between the foils was also 0.015 inches. The side rails of the frame were constructed of 1 x 1-inch bar stocks and the end rails were 0.125 x 1-inch steel. The distance in between the end rails measured 12 inches (305 mm).

Cardboard boxes for the explosive were glued to the rubber and covered the weld area alone. An explosive loading 10 g/in^2 (1.53 g/cm^2) of 40 percent Red Cross Extra Dynamite was used. This system was simultaneously detonated on both sides and water was used as the arrest system. Only a few fragments were recovered. Reducing the loading to 5 g/in^2 (0.76 g/cm^2) with the same system gave the same results. Tests were conducted with free running dynamite (10 g/in^2) and Detasheet 2 g/in^2 (0.36 g/cm^2) but both were not successful. The rubber alone did not give enough stiffness to the system, which indicated the buffer systems should be modified.

In the next tests the wire was omitted just to look at the welding of the foil alone in conjunction with various buffers. A composite buffer consisting of 1/16-inch (0.079 mm) polyethylene, 16 gage steel, and 1/16-inch neoprene rubber buffer was then used with 5 layers of 0.006-inch stainless foil. Buffers and explosive were used on both sides of the weld with the buffer extending to the end of the frame. A top plate of 16 gage steel was used to cover the buffer system and was extended over the spall rails to accelerate the whole system. The thickness of the system was matched to that of the spall rails which were fabricated of 1/2 x 1-inch (12 x 25 mm) bar stock. A partial weld was obtained which spalled about 1/2 the distance from the line of detonation. Part of the spallation problem was attributed to the water arrest system.

To eliminate the variable of the water arrest system, the next series of tests were conducted on solid anvils. Also, a soft aluminum buffer, 0.125

inches (3.18 mm) thick, was used in contact with the foil. A rubber backing was used on the aluminum. For the first of these tests the wires were omitted just to determine loading parameters. At a load of 10 g/in^2 of 40 percent Red Cross Extra dynamite a weld was obtained with 0.006-inch stainless steel foil and a 0.015-inch standoff.

The same buffer and cover system was then used with 4 layers of 0.006-inch stainless steel foil and 3 layers of 0.010-inch diameter tungsten wire at a volume percent loading of 39 percent. Welding was effected at a loading of 16 g/in^2 (2.45 g/cm^2) of 40 percent Red Cross Extra dynamite.

At this point the first tests with the C129Y alloy and TZM wire were initiated. The first foil thickness that was available was the 0.011-inch stock. The 0.020-inch TZM molybdenum wire that was to be used with this foil had not been received so the tests were conducted with 0.014-inch wire. A spacing of 0.030 (0.76 mm) inches was used on the wires with a standoff distance of 0.030 inches between foil layers. With 3 layers of foil and 2 layers of wire the volume percent wire loading was 23 percent. The same buffer system was used as for the stainless steel, i.e. 0.125-inch aluminum glued to the foil and 1/16-inch rubber glued to the aluminum with 16 gage steel cover plates. This first weld with the C129Y alloy was relatively good with some spallation on the run out and a small area of non-bond at the start of the weld.

To solve the problem of non-bond at run in and spall at the end an envelope buffer system was used similar to that used by O. Reece[2]. The buffer system was extended to 11-1/2 inches (292 mm) and then positioned so it extended 1/2-inch over the start of the weld and 1-inch over the end. The rubber on the bottom buffer was omitted and a 14 gage steel plate substituted to make up the desired overall thickness. The cover plates were also extended to coincide with the length of the buffer system. The foil and wire were the same. A small area of non-bond was present on the lead in and the envelope system worked fairly well, although a few spallation cracks were present. Wire gathering was present with some pinhole burnout. The pinholing was present only on one side. The plate was not flat but was dished at the lead in edge, which is a common occurrance with thin welds conducted on a solid anvil. Explosive

loading was maintained at 16 g/in^2 of the 40 percent Red Cross Extra dynamite.

The volume percent of wire was then increased from 23 to 32 percent and the test repeated. A large area of the run out end of the composite sheared away and wire gathering again was present about the last 1/3 of the weld with respect to detonation front. Metallography indicated that incomplete bonding of the upper foil had not taken place. The spallation at the run out end of the weld appeared to be associated with the wire gathering. Also, the envelope system still gave cracks in the foil, which indicated that momentum arrestors should be used on the inner foil layers.

Rather than repeating the tests with the expensive columbium alloy and TZM wire to solve the problems of spall and wire gathering, brass foil and tungsten wire were used. In the first test the steel cover plates were bolted to the side frames rather than just being glued and taped as was done previously. The width of the side frames was increased from 1 to 1-1/2 inches. The volume percent loading of the 0.010-inch diameter tungsten wire was reduced to 18 percent and three layers of 0.006-inch brass used. The buffer system was left the same. To insure that the explosive loading was not too light, the charge was increased to 17 g/in^2 (2.6 g/cm^2) of the 40 percent Red Cross Extra dynamite. Results of this test were mixed with no wire gathering occurring. Bolting the cover plates to the frame plus butting the buffer system against the end rails apparently eliminated this problem. The weld spalled about 2/3 the distance from the run in edges and several longitudinal cracks were present. Of main concern was that the top foil layers had broken loose even though there was evidence of jetting.

Welding of the top foil layer was of concern since in the tests with the C129Y alloy and the one with the brass imperfect welding had taken place. Since the top buffer system was comprised of steel, rubber, and then aluminum, it was decided to eliminate the material with the greatest mismatch in impedance, which was the rubber. The same test was repeated with the brass and the tungsten with a 3/16-inch (4.76 mm) thick steel plate being used as the top of the buffer with a thin 1/32-inch piece of soft aluminum against the first foil

layer. As before, the buffer was glued together using double sided tape to prevent air pockets. One inch wide momentum arrestors were glued to the ends of the foils as were 1/2-inch run in tabs. The length of the frame was increased by one inch to accomodate the tabs. The top foil layer was sporadically welded again and spallation and cracking of the weld occurred. The spallation and cracking were attributed to the low ductility of the cold rolled brass.

To insure that the welding of the top foil layer was not a matter of explosive loading another test was conducted using the same basic configuration with the brass and tungsten but increasing the loading to 19 g/in^2 (2.9 g/cm^2) of 40 percent Red Cross Extra dynamite. Again the top foil layer was not welded although the wires were welded to the second layer and jetting had taken place on the top foil. In this test the wire had been increased so the top layer would see approximately an area of tungsten amounting to 50 percent. This test confirmed that the problem was not welding parameters with respect to standoff distance or explosive loading but rather one of impedance mismatch.

An analysis using elastic wave theory on transmitted, reflected and incident waves is presented in Appendix 2. Although the theory is for the elastic reactions, prior experience has shown that predictions on weldability can be made using this approach. Any time a tensile component occurs behind the point of impact due to rarefacted waves, welding becomes difficult and in some instances impossible.

Since the mismatch in the C129Y alloy, TZM molybdenum and aluminum buffer was not as great as with the brass-tungsten wire, another series of tests were first conducted to see if an adjustment in welding parameters would overcome the non-bond problem in the top foil layer. The thinner 0.006-inch thick foil had been delivered at this point so these tests were with this thickness foil and 0.014-inch diameter TZM molybdenum wire. The explosive welding parameters with respect to standoff and loading were determined first with the thinner foil. A standoff of 0.018 inches (0.45 mm) was used which was the same as for the brass. A volume percent wire loading of 30 percent and an explosive charge

of 18 g/in^2 (2.75 g/cm^2) was used. Three layers of foil and two of wire were used with the same buffer system as used for the last of the brass-tungsten tests. In this test wire gathering was present even with the cover plates bolted to the side frames and the buffer extended over the weld and butted against the cross frame. Metallography indicated that sporadic bonding of the top layer had occurred.

In the next test the number of foil layers was increased to five and the wire layers to four. The same standoff distance was used between foil layers. Momentum arrestor and run in tabs were glued in place as in the previous test. A volume percent wire loading of 33 percent and an explosive charge of 19 g/in^2 of 40 percent Red Cross Extra dynamite were used. The cover plate-buffer arrangement was the same as before. At a higher explosive loading the results were better with respect to the bonding of the top foil. One more similar test was conducted at a higher loading of 21 g/in^2 (3.22 g/cm^2) and using a thicker top foil (0.011-inch) in an effort to attenuate the reflected wave. Again the top foil was incompletely bonded and cracking started along the length of the wire.

Since the parameters could not be adjusted to compensated to prevent the non-bond problem with the top foil layer and still have a soft buffer to allow flow around the wire without gross deformation of the wires, the next step was to design the system to alleviate reflected tensile components. The approach was to use an intermediate foil between the top layer and the buffer which was termed a "dummy" since it was not to be bonded.

In this manner impedance matching between the buffer and top foil is matched and reflected tensile waves interacting behind the collapse point are minimized. A test was then set up using three layers of 0.006-inch thick C129Y foil and two layers of 0.014-inch diameter TZM wire at a volume loading of 30 percent. The "dummy" layer of C129Y alloy attached to the buffer system with dual sided tape. A 0.006-inch foil was used for this layer. The opposing faces of the first foil layer to be welded and the dummy were painted with high-temperature aluminum paint to prevent bonding. Run in tabs and momentum arres-

tors were used as before. At an explosive loading of 21 g/in^2 a fairly good weld was obtained. The center portion along the length was entirely bonded with some non-bond areas along the sides between the first and second foil layers. Some wire gathering was present even though the cover plates were bolted to the side frames and the buffer was butted against the cross supports. The frame length had been extended to 13 inches between cross supports for this test. Some wire flattening was observed in this test.

The next test was concerned with reducing the mass of the buffer system to reduce wire flattening and using an inexpensive material for the "dummy" foil layer. Stainless steel foil 0.006 inches was substituted for the C129Y alloy "dummy" layer. The 3/16-inch thick steel portion of the buffer was removed and 0.051-inch (0.13 mm) thick steel substituted. Other than these modifications the test was the same as the one conducted before. The explosive loading was reduced from 21 to 20 g/in^2 of 40 percent Red Cross Extra dynamite.

Considerable warpage of the composite was present after welding, particularly on the run out end. Wire gathering was a distinct problem in this test. Although the stainless steel "dummy" worked to give bonding of the top foil layer the warpage in the system indicated a thin buffer system was not warranted.

The next series of tests were conducted using 0.011-inch C129Y alloy foil and 0.020-inch diameter TZM molybdenum wire. This wire was supplied in 5 to 6-foot straightened lengths. Frames could not be wound as with the finer wire so procedures had to be developed to use the straightened non-coiled wire. The cross members of the frame were slotted along the flat surface to accomodate the wire at uniform spacings rather than slotting the ends. The first member of the cross pieces was of 0.125-inch steel to give rigidity whereas the subsequent members were of 0.05-inch stock. In the work with the smaller diameter wire the wire could be pushed down at the ends to give the correct standoff distance. Since each of the heavier wires was glued in the slots, there was a greater probability of breaking the glue, which meant the end or cross pieces had to compensate for the standoff distance. Also, the tensioning of the wire had to be done in the initial gluing step rather than obtaining tension later by pushing the wire down into the frame.

In the first test the wires were spaced every 0.024 inches (0.61 mm) which gave a volume percent loading of 26 percent with two wire layers and three foil layers. The buffer system consisted of first a 0.125-inch steel layer which in turn was glued to a 0.032-inch aluminum sheet followed by an 0.011-inch C129Y alloy "dummy" layer. A standoff distance of 3T or 0.33 inches (0.83 mm) was used between foil layers. After welding with a load of 20 g/in^2 (3.05 g/cm^2) of 40 percent dynamite, there were some areas of non-bond which were not restricted to the top layer. Increasing the loading to 22 g/in^2 (3.36 g/cm^2) did give acceptable welding. An 0.018-inch (0.26 mm) steel dummy plate was then substituted for the C129Y alloy plate and welding was acceptable.

Although acceptable welds had been obtained in the last two tests above, a molten zone did exist at the interface. Welding parameters were then adjusted to a standoff of 0.022 inches (2T) and 18 g/in^2 of 40 percent dynamite. An acceptable weld was obtained using these modifications to the same test setup with a steel dummy plate. There were no large melt zones in this composite between foil layers.

In all of the tests which were welded on an anvil dishing of the composite was present. The next tests were concerned with eliminating the dishing in the composite and also were looking forward to the cost of a heavy steel anvil system which could crack with each of the shots proposed in Phase II. Therefore, the concept of the explosive anvil was tried again without a water arrest system. The frame system was set on its edge on top of a 8 x 8-inch wood cant which was considered expendable. To balance the force on both sides, another cant was taped to the top edge prior to detonation. The shot was aimed so the composite would impact a soft earth bank about 50 yards from the point of detonation.

A dual buffer system was used on either side of the frame along with dual "dummy" plates. Other than the dual buffer system the test configuration was the same as used previously with the 0.011-inch C129Y foil and 0.020-inch diameter TZM molybdenum wire. An explosive loading of 9 g/in^2 (1.38 g/cm^2) was

used on both sides of the assembly. Resorting to the explosive anvil gave a relatively flat composite although some wire gathering was present. The wire gathering occurred even though 16-gage steel cover plates were bolted to the side rails and the buffer system butted against the cross pieces.

In the next test with the explosive anvil the wire loading was increased to 30 percent. Other than this change the test setup was the same. A small amount of wire gathering was present after welding. At the higher wire loading, some of the wires touched or were welded together. Although the wire had been straightened, the wires still touched in spots before welding that could not be prevented due to the inability to tension each single wire uniformly during layup.

The next test was conducted with five layers of 0.011-inch C129Y foil and four layers of 0.02-inch wire. Volume percent wire loading was 30 percent in this test. The same welding parameters were maintained as in the previous test. The composite was flat and welding was good as observed by metallography. Some wire flattening was present where the wires touched.

In the next test the wire loading was decreased to 25 volume percent, still maintaining the five layers of 0.011-inch foil and four layers of 0.020-inch diameter wire. Although the explosive loading was the same, welding was sporadic. A new lot of 40 percent dynamite was used with this test. A check was run on the detonation velocity and showed the new lot to have a velocity of 2800 m/sec, which was about 600 m/sec lower than the previous lot. The difference in velocity in packed type of explosives is a universal problem whether in dynamites or purer explosives such as nitro guanadine.

Exactly the same test setup was used again and the dynamite loading increased to 11 g/in^2 (1.68 g/cm^2) to compensate for the lower energy output of the new lot of dynamite. With this adjustment, a good composite was obtained that was welded without wire distortion or gathering.

A test was then conducted with the heavy 0.032-inch diameter TZM molybdenum wire and 0.017-inch thick foil. Three layers of foil were used with two layers of wire at a wire loading of 33 percent. A standoff distance of 0.04

inches (0.1 mm) was used and explosive loading of 11 g/in^2 of 40 percent dynamite on either side. The buffer system was the same as that established for the thinner foils. A 0.018-inch dummy layer was used on either side. A relatively good composite was obtained that did have some surface jetting between the wires.

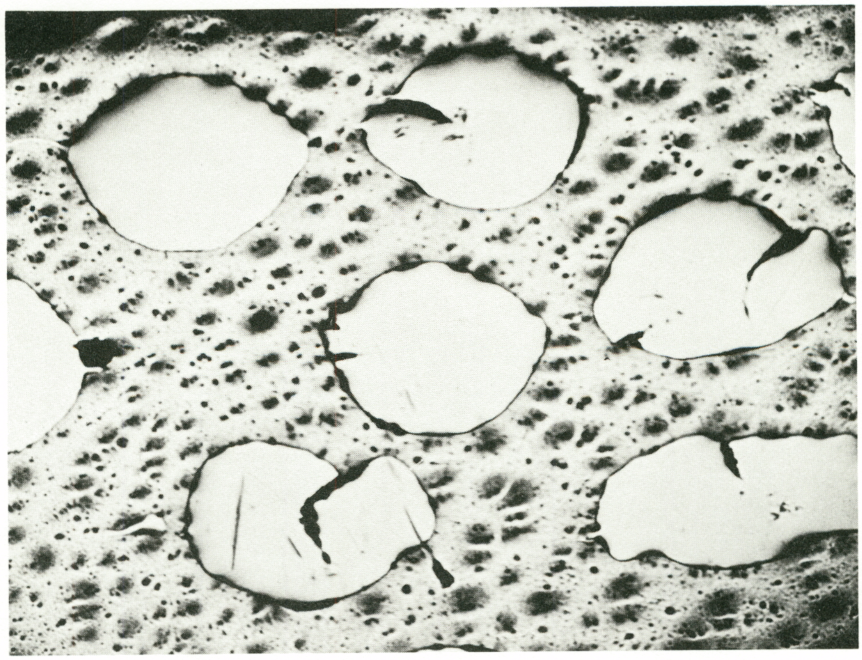
The number of foil layers was increased to five and the wire layers to four with a wire loading of 37 percent. A good flat composite was obtained to an explosive loading of 11 g/in^2 of 40 percent dynamite on both sides. Metallography indicated small non-bond zones adjacent to the wires in some cases. These non-bond areas were present where the foil had not completely flowed around the wire. Since acceptable bonds had been obtained with all three combinations of foil thickness and wire diameters, Phase II of the program was initiated at the sponsor's request.

2.3 Evaluation of Phase I Welds

The irregular surface on the composites ruled out ultrasonic inspection techniques for determining non-bonded areas. Also, the differences in density and sonic velocity of the C129Y alloy and TZM molybdenum give difficult-to-interpret results in ultrasonic inspection. Since the ultrasonic method was to be confirmed by metallography it was decided to metallographically inspect each weld. This type of inspection also allows an evaluation of wire flattening and cracking as well as the state of bonding.

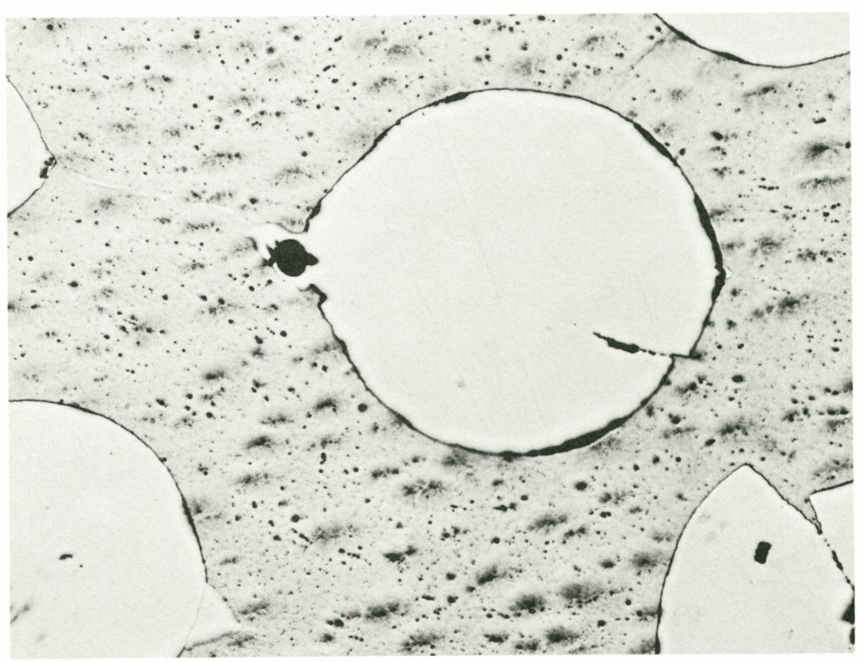
Use of the 0.014-inch diameter TZM wire and 0.006-inch foil at optimum welding conditions gave the results shown in Figure 3. This composite was made at an explosive loading of 19 g/in^2 of 40 percent Red Cross Extra dynamite welded on a steel anvil. Wire loading was at 34 volume percent and a standoff of 0.018 inches was used between foils. The buffer system consisted of a 0.188-inch thick steel plate glued to a 0.032-inch soft aluminum which in turn was glued to a 0.006-inch C129Y foil as a dummy layer.

As can be seen by an inspection of Figure 3, longitudinal cracks were generated in the wire. There are pockets of jet entrapment between the foil layers which are discontinuous. More wire flattening is present when the wire



As Polished 50X

Figure 3. Photomicrograph of Composite Made With 0.014-inch TZM Wire and 0.006-inch Cl29Y Foil.



As Polished 100X

Figure 4. Photomicrograph of Composite Made With 0.020-inch TZM Wire and 0.011-inch Cl29Y Foil.

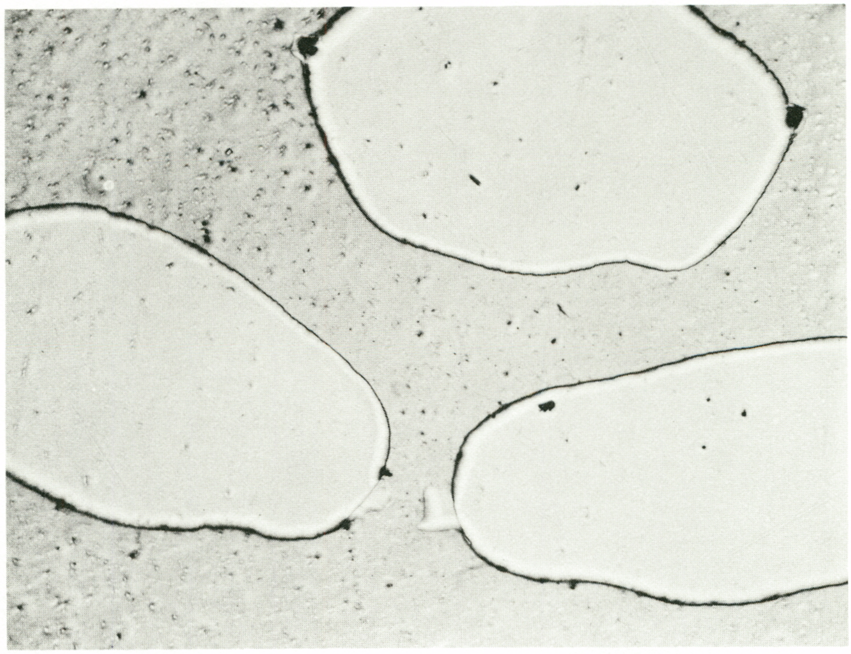
layers are not staggered but are on top of one another.

A few different features were observed as the foil thickness and wire diameter were increased to 0.011 inches and 0.02 inches respectively. The amount of jetting had to be controlled more by adjusting the standoff and amount of explosive. Wire cracking along the length still was present as is shown in Figure 4. Another factor, although it is minimal in Figure 4, was the formation of a solid melt layer between the foil layers. Some voids were present occasionally along the side of the wire where the jet running down the diameter of the wire meets the foil interface.

Use of a steel anvil during the welding of the composites with 0.011-inch C129Y foil and 0.020-inch diameter wire resulted in wire flattening, as is shown in Figure 5. Some longitudinal cracking of the composites was present when heavy steel anvils were used.

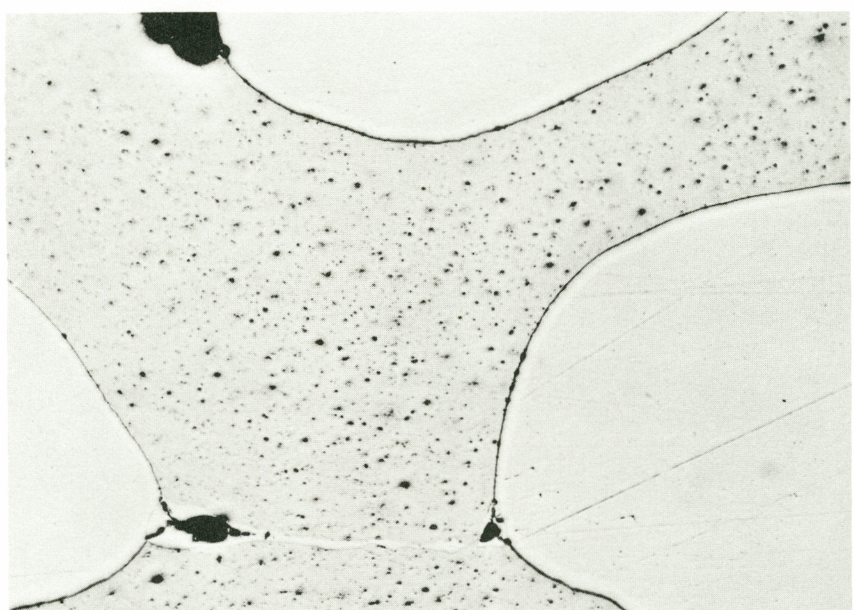
Welds made with 0.032-inch diameter wire and 0.017-inch foil were characterized by melt and void pockets adjacent to the wire, as is shown in Figure 6. The size of the voids varied with no particular pattern being established. There was more of a tendency for the large diameter wire to deform rather than to crack along the length. More melt was observed along the weld interface with the larger diameter wire. The melt is the result of jet interaction from the parallel plate jet as well as the jet running down the sides of the wire, which is essentially a preset angle weld. In areas of heavy jet formation, the melt zones generally contained voids such as is shown in Figure 6.

The metallographic evaluation of the composites would indicate that the composites with 0.014 and 0.020-inch diameter wire would contain cracks in the wire. These could act as a built-in flaw. However, in some composite systems such as the Borals, longitudinal cracking of the filament is a common feature. Voids and melt pockets in the composites with the large 0.032-inch diameter wire composites is a more serious problem. In these composites, the voids act as an internal stress riser and in use would grow in size when subjected to stress. The melt zones between foil layers might be partially eliminated by subsequent heat treatment or use but are still a zone of weakness.



As Polished 100X

Figure 5. Photomicrograph of Composite Made with 0.020-inch TZM Wire and 0.011-inch C129Y on a Steel Anvil.



As Polished 100X

Figure 6. Photomicrograph of Composite Made with 0.032-inch TZM Wire and 0.017-inch C129Y Foil.

For actual applications, the composites with the smaller diameter 0.014 and 0.020-inch wire would be preferable since there is a high incidence of melt zones and voids in composites with larger diameter wire. The cracking problem in the smaller diameter wire might be alleviated by compromising the strength of the wire by increasing the ductility so the wire would deform rather than crack.

Based upon the metallographic inspection of the various welds the welding parameters that gave the best results for each wire diameter and foil thickness are as follows:

Foil-Wire Combination	Standoff Distance, in.	Explosive Loading, g/in^2 (1)	Buffer System (3)
0.017-in Foil 0.032-in Wire	0.04	11 (1)	0.125"Steel 0.031"Al 0.018"Steel
0.011-in Foil 0.020-in Wire	0.022 to 0.033	11 (1)	0.125"Steel 0.031"Al 0.018"Steel
0.006-in Foil 0.014-in Wire	0.018	21 (2)	0.250"Steel 0.031"Al 0.011"C129Y

(1) Loading on both sides (2800 m/sec 40% dynamite)

(2) Loading on one side only (3400 m/sec 40% dynamite)

(3) Buffer system from explosive to weld

III. PHASE II SCALEUP TO 10 x 20-INCH COMPOSITES

3.1 Scaleup Considerations

Several factors were considered in scaling up from 5 x 10-inch to 10 x 20-inch composites. First was the anvil arrangement to be used. All of the small scale tests conducted with the explosive on one side only and with a steel anvil on the other did not have the desired degree of flatness. Another problem was the propensity to develop longitudinal cracks associated when welding on a steel anvil. Using an explosive anvil which in reality is simultaneous welding from both sides gave a much flatter composite without a large amount of distortion. A secondary consideration was the steel anvil itself which would have to be at least three inches thick and would probably have to be considered expendable with each experiment as thick plate stock is subject to cracking. In several of the small scale experiments, the cover sheet used over the composite assembly welded to the steel anvil which again indicated that the anvil would be good for only one or two experiments.

Based upon these observations, it was decided to use the explosive anvil approach since it had worked so well in the small scale experiments. The biggest disadvantage was the precision required to obtain simultaneous detonation of the explosive on both sides. This disadvantage was not a major problem.

The next consideration was the dimensions of the frames required for welding the larger composites. Most of the small frames that gave good results were constructed with side rails that were 5/8 x 1-1/2 inches (16 x 29 mm) in cross-section. The end pieces were multi layered with the first cross piece being 1/8 x 1-inch (3 x 25 mm) in cross section and the thickness of the subsequent layers being dictated by the standoff distance required between the foil layers.

The side rails not only have the function of holding the assembly in place for winding the wires but also preventing spallation along the sides of the composite. Increasing the length allows a greater bending moment if the same cross-section is maintained. The main static force that has to be coun-

teracted by the side rails is that induced by tensioning the wire during the winding operation. The side rails also have to be accelerated during the welding phase so the rate of travel is the same as that of the weld. This is accomplished by placing cover sheets over the entire assembly and bolting them to the side rails. The explosive covers the entire area including the side rails to give the acceleration.

The end pieces on the frame have to be rigid enough to resist bending when the wire is tensioned so the tension is uniform on each individual wire. When the whole frame is assembled, it has to be rigid enough to hold the foils in place along the entire edge to help maintain the standoff distance between the foils. Intimate contact is necessary between the edge of the composite and side rails during welding to prevent spall cracks. Any bending of the side rails defeats these functions of the frame.

Maintaining a constant standoff distance in large explosive bonds is a problem since the material tends to sag under its own weight. This is one advantage in using an explosive anvil as the foils are on edge and the wires help to hold the foils in place without resorting to internal standoffs such as are used on large plate explosion bonds. The degree of flatness of the foils is definitely a problem particularly as the thickness decreases. In the small scale welds, the edge warpage is much easier to control since the foils can be cut transverse to the rolling direction to give a relatively flat sheet to start with. With the 10 x 20-inch sheets the edge warpage has to be compensated for by using multiple standoffs along the edge, which in turn are entrapped and act as jet arrestors. Arresting the jet tends to give tears or burnouts at the point of entrapment.

Increasing the area over which the explosive is placed also requires a more rigid explosive confinement system when dual welding charges are used. In the small scale tests, 1/4-inch (6 mm) thick plywood was adequate to cover the explosive. To prevent cracking of the compacted dynamite in the larger size welds, it was realized that thicker plywood would be required. Increasing the confinement of the explosive can result in increased detonation velocities and greater energy releases. Therefore, the possibility of adjusting

the explosive loading had to be considered.

3.2 Experimental Approach

In the first of the scaleup tests a mockup was made in which no wire was used. The side rails were fabricated from 5/8 x 1-1/2-inch stock and the end pieces of 1/8 x 1-inch material. The distance between end pieces was 22 inches (560 mm). The buffer system on both sides consisted of 0.125-inch steel overlying a 0.03-inch aluminum and 0.018-inch steel. These were all glued together using dual sided tape. Two pieces of 0.018-inch steel foil were used for the weld. The faces between the steel foil in the buffer system and the top of the steel foil was painted to prevent welding. Cover plates of 16 gage steel were bolted to both sides. Of interest was the spallation that could occur if the side rails were not heavy enough. An explosive loading of 11 g/in^2 was used on both sides which was confined by 3/8-inch (9.5 mm) plywood.

The foils were warped after welding and the welding was sporadic. The foils did not spall at the edges, which indicated that confinement was adequate with respect to spalling but not sufficient to prevent warping.

Another test was conducted in which the side rails were made from 5/8 x 3-inch (16 x 76 mm) steel stock. The weld area in the prior test was the same as the frame cavity, and part of the warpage was thought to be due to the weld striking the end piece as well as insufficient support. Therefore, the distance between the end bars was increased to 24 inches (604 mm). The end pieces were made from 1/8 x 1-1/2-inch (3 x 38 mm) stock so the overall length of the assembly was 27 inches (685 mm). The buffer system was the same as in the previous test, only the length was increased by an inch so the total length of the buffer system was 23 inches (58.5 mm). To gain the effect of a wire layer, a 0.018-inch foil was placed at the center that was 10 x 27 inches (254 x 685 mm) long and was glued and braced to the end pieces with epoxy cement. Two sheets of 0.018-inch steel foil were then used with a 0.030 inch standoff between them. An explosive loading on both sides of 11 g/in^2 of 40 percent dynamite was used. The charge was confined with 3/8-inch plywood.

The purpose of the above test was to determine end spall and flatness. After firing, the weld was relatively flat, and no spall was present. The degree of flatness was much better than with the smaller cross-section side rails, so the 5/8 x 3-inch side rails were used in all subsequent tests.

Since the combination of 0.017-inch C129Y foil and 0.032-inch wire gave composites with internal flaws, the next test was set up using this combination to indicate what problems could be anticipated with a wire-foil combination, before starting with the smaller thickness and diameter wire. The width of the end pieces was increased from 1-1/2 to 2 inches (38 to 51 mm) so a larger gluing area could be obtained. The overall length of the frame was then 28 inches (710 mm). The end pieces were notched on the flat side rather than the ends so the straightened lengths of wire could be positioned. A wire loading of 34 volume percent was used. Two layers of wire and three layers of foil were used. The standoff distance between the foil layers was 0.04 inches, which had been determined in the small scale tests. In making the end pieces the holes attaching the end pieces to the side rails were made in an oval configuration so the pieces could be positioned to give staggering of the wire layers.

One row of wires was first glued in place at one end only using five-minute epoxy. The next cross plate was then placed over the wires and glued with epoxy. The glue was then allowed to dry. The wires were pulled into their corresponding slot on the other end of the frames and bent over the end to achieve tensioning. Five-minute epoxy was used to hold the wire at this stage. After a complete row of wire had been glued in place the next cross piece was placed over the wires and glued. At this point, those wires that were still loose were pulled again to achieve more tension.

A foil was placed on top of the first layer of wires and the procedure repeated for the second layer. It became apparent during the lay up of this composite that the "straightened" lengths of wire were not truly straight. Also, tensioning was very difficult and time-consuming due primarily to the length of time required for the glue to harden. Even with all the precautions

taken to pull and tension each wire some touching of the wires was present after layup. With the wires touching there is no way of achieving a bond between the wires and also the jet can be trapped at these points which can lead to non-bond and burnout spots.

Steel dummy plates were used with this weld and the opposing faces of the dummy sheet and first foil layer were painted to prevent bonding. The buffer system was composed of 0.125-inch steel, 031-inch aluminum plus the 0.018-inch steel dummy plates. The buffer systems were glued together using double sided tape. One-inch run in tabs and momentum arrestors were used on each end of the foil. These 1 x 10-inch (25 x 254 mm) pieces were spot welded to the foil using small steel foil pieces, which were required to hold them firmly in position. The spot welding was a departure from the gluing used in the small scale tests since gluing was not adequate for the larger sheets.

The buffer system was 23 inches long so it could envelope the weld area. The run in end of the weld and buffer were matched so at run out a 1-inch overlap of the buffer was present. The run out end of the buffer system was butted against the cross supports to transfer momentum and help prevent wire gathering. Finally, 16-gage steel cover plates were bolted to both sides of the assembly so they covered the buffer system and the spall rails. The dimensions of the cover plates were 16 x 23 inches.

The cardboard dynamite boxes were glued with double sided tape to the cover plates and the charges were then loaded. As in the small scale tests and the trial runs, the charge covered the side spall rails so they would be accelerated. The charges were covered with 3/8-inch plywood to hold the dynamite firmly in place. A loading of 11 g/in^2 of 40 percent dynamite was used. Figure 7 is a picture of the assembly just prior to detonation.

After detonation, the dummy plates on both sides had welded to the composite in various areas, particularly on the run-out part of the composite. An area of non-bond was present on one side of the composite near the run-out end. Even though the wires had been glued and braced in place, some of them

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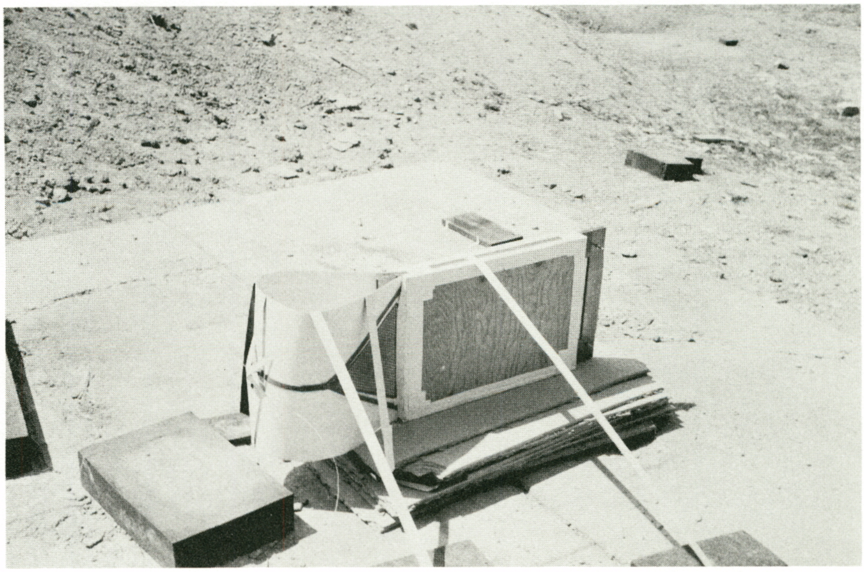

Figure 7. Large Scale Composite Welding Assembly Just Prior to Detonation.

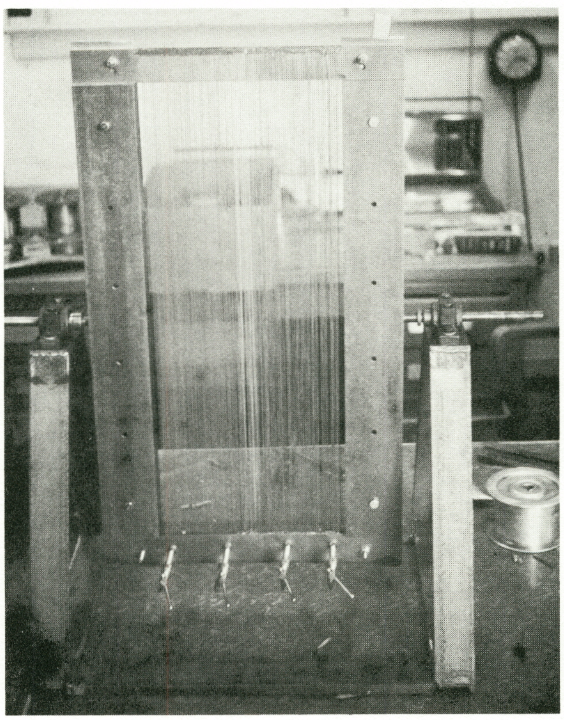

Figure 8. Winding Arrangement With Two Frames Set Back to Back.

came loose during welding to give wire cross-over spots. The degree of flatness immediately after welding was fairly good. However, the weld was very hot immediately after welding and while it was cooling it achieved a definite bow. The cooling was accompanied by loud noises as if it were cracking during cooling.

After welding, the non-bonded portions of the steel dummy plate were cut from the weld and the remainder dissolved away in nitric acid so the composite could be inspected. There was no wire gathering present in the weld. Some pinholes were present where the wires had crossed over during welding and trapped the jet. A few longitudinal cracks were present in the top foil layers in the small area of non-bond on one side at the run out end.

This practice weld with the heavy C129Y foil and large diameter TZM wire did indicate several modifications. First, the straightened lengths of wire were not straight enough to use in large scale welds since they could not be adequately tensioned and held in place. This was of considerable importance since the 0.020-inch diameter wire used in the small scale tests was also provided in straightened lengths.

Second, the paint on the top foil layers of the composite and the opposing face of the dummy layers was not adequate to prevent welding of the two. Since the welding of the dummy layers was sporadic it lead to warping of the composite due to the differential in thermal expansion and cooling rates.

As a result of this test the next series of tests were concerned with the prevention of welding the dummy layers to the composite. In the first of these tests alternate layers of steel were used to simulate the composite. The frame dimensions were kept the same. Four layers of 14-gage steel foil were cut 9-1/2 x 28 inches (242 x 710 mm) to simulate the wire layers and were attached to the end pieces using gluing and alternate braces. Five layers of 8-gage steel foil were used to simulate the foil that would be used in the composite. These were cut to dimensions of 10 x 22 inches (254 x 560 mm) and placed at standoffs of 0.024 inches (0.61 mm). The dummy layers and buffer system were the same as used before as were the 16-gage steel cover plates.

Opposing faces of the top foil layers and dummy sheets were painted with enamel. Several layers of enamel were sprayed on rather than simply using one layer as in the small scale tests ana the one large scale test with the C129Y alloy and TZM wire. The explosive loading and confinement system was kept constant for this test.

Sporadic welding was observed between the dummy layer and the top foil layers. Welding throughout the whole system was sporadic, which was attributed to the flatness of the foil layers. The steel foil came in rolled stock and required flattening before welding. The flattening operation did not remove all of the set in the foils.

Another test was then conducted in which the same thicknesses of foil were used. The opposing faces of the dummy sheets and top foil layers were again painted with enamel. The surfaces were then dusted with -100 mesh aluminum oxide while the paint was still wet. The actual setup for the buffer and cover plates was the same as before.

No bonding occurred between the dummy layers and the top foil layers in this test, indicating that the alumina was adequate to prevent bonding. Actual bonding of the foil layers was poor, which again was a function of maintaining the standoff.

One more trial run was made with steel foils. In this test the 0.014-inch steel foil was cut into 1/2-inch wide strips and glued and braced at the end of the frames. The alternate steel strips were staggered. Five layers of 0.008-inch steel foil were used with four layers of 0.014-inch steel foil strips. Dimensions of the foil, buffer system and cover plates were the same as before, as was the explosive loading. Opposing dummy and top foil faces were painted and dusted with -100 mesh aluminum oxide as in the previous test.

No welding took place between the top foil layers and the dummy sheets. The actual composite was flat. A spall did take place on the run-out end but this was anticipated since no provision had been made for momentum arrestors. Several burnouts were present between the strips, which was attributed to the differential in standoff distance that was present since the foils were not

absolutely flat. One change was made in the detonation procedure for this test. Rather than setting the frame on several layers of Celotex for detonation as is shown in Figure 7, the assembly was set about 8 inches above the ground with the first and last 2 inches resting on wood blocks. This allowed the bottom side rail to separate freely. These trial shots did indicate that flat welds could be achieved with the larger dimension composites and that welding could be prevented between the dummy and foil layers by the simple expedient of dusting the painted surfaces with aluminum oxide.

At this stage it was decided to proceed with the production of the 10 x 20-inch TZM molybdenum wire reinforced C129Y columbium alloy composite. Two frames were simultaneously wound with 0.014-inch molybdenum wire. A winding frame was constructed as is shown in Figure 8 for winding. The cross supports at the end were notched every 0.037 inches (0.94 mm) on the end so the wire could be positioned. At this separation the volume of wire was 30 percent. The thickness of the cross supports for the first layer was 0.125 inches to give the desired rigidity. Each subsequent cross piece was made from 0.031-inch steel stock to give the correct separation distance between the wires. The first cross support was 1.6 inches wide and the width was increased 0.1 inches for each subsequent support so the loops over the ends of the frame would not contact one another. Five layers of wire were used with six layers of 0.008-inch foil to give a thickness of approximately 0.08 inches in the final composite.

The bolt holes in the thin cross supports were oval so they could be positioned to stagger each subsequent layer of wire. As each layer of wire was completed, epoxy was placed over the ends, the next support positioned and 'C' clamps applied to the support until the epoxy dried. This procedure permanently held the wires tightly in position.

One serious problem arose during the winding operation. The first lot of 0.014-inch wire received from NASA was exhausted part way through wrapping the first layer. On starting to use wire from the second lot, breakage occurred as the wire was tensioned over the ends of the frame. The wire split and fractured when it was bent, regardless of how much care was exercised in wrapping

the frame. The wire had been furnished to meet specifications set forth by NASA. On checking with the original vendor, it was found that the wire did meet specifications but that it had been processed differently. Therefore, several heat treatments were conducted to find how the wire could be annealed and still meet the strength requirements and increase the ductility to withstand the winding operation. An additional anneal for one hour in vacuum at 1000°C did give a bendable wire with tensile strengths in excess of 300,000 psi. Shorter periods of time at 1000°C and lower temperatures gave wire that still broke on bending. The wire was returned to the vendor for heat treating.

As each layer of wire was finished the next foil layer was added so the wire could be wrapped over the foil. One inch stainless steel run-in tabs and momentum arrestors were spot welded to the ends of the foil. Small cardboard standoffs were positioned at intervals along the edge of each foil to help keep the foils separated. After the last wire wrap was made the final cross support of 0.125-inch steel was bolted and glued in place.

There was a tendency for the first layers to lose some of their tension during winding. This indicated that some bending stress was introduced as each subsequent wire layer was added. The bending was in the end supports which were intergally glued together. However, the slight loosening was not enough to allow the wires to touch. After the last cross support was added, the wires between the two frames were cut with a small silicon carbide wheel.

After the frames had been cut apart the foils were positioned so they were centered in the frame. The last foil layer was added to each side and the buffer systems placed so they butted against one end. Opposing faces of the last foil layers and the dummy sheet which was attached to the buffer system had been painted and dusted with aluminum oxide. The buffer system enveloped the run out end of the weld and started at the point of run in. After placement of the buffer system, 16-gage steel cover plates were then bolted to the side frames. Bolts were placed every three inches along the edge to attach the cover plates.

For the first test with this wire-foil combination, an explosive loading of 11 g/in^2 of 40 percent dynamite was used on each side. One-half inch plywood covers were used over the explosive. In this test, the composite was relatively flat after welding but wire gathering was very much in evidence. The wire started to gather only 8 to 10 inches into the weld from the leading edge. Pinholing was present in the large area where wire gathering was present. Several non-bond areas were also present which were in the form of blisters ranging from 1/4 to 1 inch in diameter.

The wire gathering was not anticipated since the same procedures were used in this test that had been developed in Phase I of the program to prevent this occurance, i.e., butting the buffer assembly against the end plates and bolting the cover plates to the side rails. Also, on the previous test with the heavy C129Y foil and large diameter TZM molybdenum wire, no gathering was evident.

Prior to conducting the next test, the cover plates were removed from the assembly and the buffer system inspected to be sure that it butted against the end plates. The cover plates were then bolted back in place and the explosive boxes added. The explosive loading was kept the same or 11 g/in^2 on each side. Covers of 3/8-inch plywood were used over the explosive.

In this test, the line wave generators were positioned at an angle of about 45° relative to the plane of the weld as it was thought that the blast wave from the detonation system could have prematurely broken the wires on the lead-on end. The remainder of the procedures were the same.

This composite was even worse with less planarity and some edge cracking present in the last 10 inches of the sheet. Wire gathering again was present starting at about the same distance in from the leading edge. Several non-bond areas were present in the form of blisters.

The problems in the above tests with the wire gathering did not indicate that the degree of tensioning the wire was at fault since the amount and point at which gathering started was the same on both sides of the composites. The fact that the buffer system contacts the run-out edge should keep tension on

the wire as the plates are collapsing. Non-bond in the form of blisters could be non-uniform collapse of the sheets caused by the original non-planarity of the foils.

In the next tests 0.020-inch TZM molybdenum wire and 0.011-inch C129Y columbium foil were used. Essentially the same system was used to wind the frames as with the finer wire. The end notches were placed every 0.067 (0.17 mm) inches which gives a wire loading of 25 volume percent with 4 layers of wire and five layers of foil being used. The standoff distance between foil layers was 0.022 inches or the same as that used in the small scale tests with this combination of wire and foil.

Winding of the heavier 0.020-inch wire was more difficult than the finer wire. The wire split along the length at almost every bend so extra care had to be exercised to be sure that the wire was tensioned before it was bent over the cross supports. Also, portions of this wire had apparently been wound on a small diameter spool during processing which required extra tensioning to remove the set in the wire. Even with all the precautions taken some of the wires still touched after winding. To eliminate the touching problems, one of the wires that touched was removed after the ends of the wire had been glued with the next cross-support in place.

One-inch wide stainless steel tabs were spot welded to the ends of the foils for run in tabs and momentum arrestors. The buffer system and weld stop between the dummies and top foil layer were the same as before. The 16-gage cover plates were cut to cover the entire weld area rather than just being over the dummy system. This was done to protect the wire from blast effects associated with the line wave detonation system.

Another modification was to put Detasheet strips into the dynamite along the spall rails. These strips extended 3 inches into the dynamite and were used in an attempt to move the side rails faster than the rest of the assembly so tension would remain on the wires even after the wires were severed from the supports at the leading edge. Both of these tests were conducted using an explosive loading of 10.5 g/in^2 (1.6 g/cm^2) of 40 percent dynamite covered with 3/8-inch plywood.

Wire gathering was a problem in these tests even though the wire diameter was greater. The start of the gathering was about the same distance into the weld as in the test with the finer wire (about 8 inches). Burnouts were associated with the wire gathering where touching of the wires took place. In some areas, particularly near the end of the weld, cracks developed between the pinholes caused by the jet escaping.

Several areas of non-bond were present in the form of blisters but most of those were larger than those associated with the thinner foil. The degree of planarity was relatively good with one composite while the other was warped to some extent.

Another test was then set up in which only one frame was wound with six layers of 0.014-inch diameter wire. Five 0.008-inch foils were used in between the wires and two 0.011-inch foils used for the top layers. Standoffs between the 0.008-inch foils were 0.024 inches and for the top layers were 0.022 inches. Layup procedures of the buffers and cover plates were not changed.

Winding of a single frame did require a few changes on frame dimensions. The first wrap around the end pieces had to be centered. However, if 0.125-inch stock were used for the first cross-pieces as had been done with the other frames, the correct standoff distance would not be obtained between the two center wraps. Using a cross-piece of thinner stock would result in bending if the width were maintained at 1.6 inches for the first cross-piece. Therefore the width of the first 0.03-inch thick cross-piece was increased to 2.50 inches. Notches were milled into the end of the cross piece every 0.048 inches (0.12 mm) to give a wire loading of 25 volume percent. The wire loading was decreased so a greater area would be available for welding in order to reduce the blistering type of non-bond.

Subsequent cross pieces were increased in width by 1/4 inch and were added on one side only. Shims were glued in place on the opposing side using epoxy cement. After the last wrap of wire was completed 0.125-inch cross pieces were added to provide a large enough area for the buffer system to

butt up against. The final cross pieces were three inches in width. With the extra width, the side rails were increased two inches in length to accommodate the cross pieces. One advantage of winding a single frame was that the tension on the wire appeared to be more uniform than on the dual wound frames.

The buffer and cover plate systems were not changed. One change in the detonation system was to increase the length of the Detasheet strips into the dynamite over the spall rails by an additional inch. The dynamite loading was 10.5 g/in^2 and was covered with 3/8-inch plywood as in prior tests.

This particular composite was the best produced but still had several of the same flaws. First, wire gathering occurred but was removed about 2 inches further down the weld from the line of detonation. This gave a composite in which only about 1/2 the sheet had serious wire gathering. The number and size of non-bond areas was reduced by lowering the volume percent of wire. Warpage was minimal although there appeared to be some spall in the underlying foil sheets, particularly on the run out end.

3.3 Analysis of Problems Encountered in Phase II

The most serious problem encountered in Phase II was the wire gathering that occurred with the 0.014 and 0.020-inch wire. With the larger 0.032-inch wire the wrinkling effect was not noted but cross-over of the wires did take place and may in part be related. The heavier wire would resist the bending to a greater degree than the finer diameter wires, thus the crossing over rather than bending in sine wave form.

Both of the finer diameter wires were under considerable tension to keep them straight and from touching one another. Any release of the tension would result in the wires springing back. During the initial 8 to 12 inches of welding the wires were in the correct position with the gathering appearing in the remainder of the weld. It was not a gradual buildup but starts almost simultaneously, which indicates that the tension has to be released at that time or some other mechanism such as an oscillation type of vibration starts.

The main mass of the buffer system is steel through which a longitudinal elastic wave can move at the rate of about 6000 m/sec disregarding attenuation. The collapse of the plates for welding occurs in the range of 2800 to 3500 m/sec. A plastic wave is also generated that can move through the steel buffer system at a rate of 4000 to 5000 m/sec, again disregarding attenuation. If both of these waves are of sufficient magnitude to reach the cross pieces at the end of the weld and break the wire at this point the release of the tension could travel back through the wires at a speed again approaching the elastic wave velocity. In this analysis the wire gathering would appear roughly about 14 inches from the starting point.

In actual welds it is appearing sooner which would indicate again that in some manner, the foils are moving faster than wire after approximately one half of the weld is made. Since the foils are not butted against the end they could move but would have to be moving faster than the buffer system or in effect would be jetting out from between the buffer. The major change between the buffer and the foils in the large scale tests was the addition of the alumina in the paint to prevent bonding. It could be that this change did lower the friction between the buffer and weld and allow movement of the foils relative to the wire.

In the one large scale weld with the heavy 0.032-inch wire actual welding of the dummy plate and weld took place which would restrict movement of the weld portion. With this weld the wrinkling of the wire did not occur, which to some extent can be attributed to the heavier cross-section.

In the welds with the smaller diameter wires, some misalighnment of the foils (about 1/4 inch) was apparent after welding even though they had been carefully aligned prior to detonation. A difference in collapse rate could account for this as well as a difference in the frictional component on either side between the dummy sheets and the top foil layers. In either event it could be possible to move the foils at different rates than the wires, with slightly different collapse rates or a pushing effect by the buffer on the foils that accelerate the foils. However, if the detonation rates in a dual

side weld were different, the flatness of the sheets would not be as good as that observed on the tests.

Another contributing cause to the wire gathering could be an oscillatory motion set up in the wire. Crossland[5] in his work on welding wire reinforced composites did note that as the length of the weld increased a sine wave shape was apparent in the wire in the longitudinal and transverse directions which he ascribed to an oscillatory movement being set up by the actual welding. As the ocean wave type of interface is obtained the wire is strained to conform to the interface and an elastic wave motion is set up by flexure which moves down the wire before it is welded. This flexural motion would increase with length. However, the oscillations are slight to start with and gain in magnitude which was not the case in the present experiments.

Breaking the wires away from the cross bars on the initiation end was also thought to be a contributing cause. Extending the cover plates to protect the wire ends from the blast effect did not alleviate the situation.

Heavier side rails were used in the large scale welds to prevent bending during winding of the frames and warping during welding. Although the areal loading of explosive on the side rails was the same as on the smaller frames, the loading may not have been adequate to give the desired acceleration. There was some difference in wire gathering as a result of detonating the dynamite on the side rails before that on the weld area, but the difference was not marked enough to indicate that this was the main problem.

Another major problem was the areas of non-bond which were primarily in the form of blisters in the top foil layers. These occurred intermittently throughout the welds with the smaller diameter wire. There was no pattern associated with the blisters to indicate irregularities in collapsing plate mode. In some instances there were more areas of non-bond on one side than on the other. Blisters in explosive welds can be trapped air or areas in which a bond was not achieved and the resulting rarefaction wave pulls the metal away in the shape of a blister.

Since there was no indication of matching marks on the dummy plates, the air entrapment could be ruled out. The blisters were simply non-bonded areas that had this form due to the rarefaction. Non-bond is the result of incorrect welding parameters with respect to standoff and amount of explosive. In the present case the explosive was uniformly packed. Also, the heavy buffer system helps to distribute the collapsing plate in uniform manner with a uniform pressure distribution. Therefore standoff distance and the tensile rarefaction indicated in Appendix I can be related to the non-bond.

The thin foils used were not flat, which leads to a non-uniform standoff distance. This can be accumulative since it was impossible to have a minimum standoff at which welding would occur. Increasing the standoff at a given explosive load makes it easier to weld to a certain point, after which tearing occurs. Therefore, there has to be a minimum and a maximum for a particular explosive loading which was the goal of welding the composites. However, this was not achieved, as the degree of non-flatness on the foils was as much as 10 times the thickness of the foil in some cases.

Tearing of the foils was another of the problems. As explained previously, tearing is associated with too great a standoff distance. Another cause of tearing spall lies in non-uniform momentum transfer to the side rails and the momentum arrestors. Non-uniform collapse of the foils in which the standoff distance is irregular probably was the main cause of the tears and spall cracks developed in the present large scale composites.

The other defect that occurred was pinholing of the outside foil layers extending down through the second layers in some instances. This defect was associated with wire gathering when two wires touched, trapping the jet which then burned through the foils to give a pinhole in the composites. In the absence of wire gathering, pinholing was not a problem.

IV. SUMMARY AND CONCLUSIONS

The ultimate goal to develop 10 x 20-inch explosively bonded composites of TZM molybdenum wire reinforced C129Y columbium composites at a 33 volume percent loading was not realized. Smaller 5 x 10-inch composites meeting the requirements of thickness and wire loading were developed. Results of the tests with the small scale composites indicated a compromise situation existed. Large diameter wires (0.032 inches) used in conjunction with 0.017-inch thick foils resulted in excessive melt between foils as well as void formation adjacent to the wire in the weld plane. Small diameter (0.014-inch) wire and thin foils (0.006 or 0.008-inch) gave good composites without molten zones or void formation, but longitudinal cracking of the wire was present.

Using 0.020-inch diameter wire with 0.011-inch thick foils gave a minimum amount of wire cracking and melt zone formation. Wire flattening was observed but this situation was not considered to be serious. Therefore, the best overall quality composites were those with the 0.020-inch diameter wire and 0.011-inch foil which contained some melt zones but did not have the larger flaws associated with the other two combinations.

Scaling up from the successful 5 x 10-inch welds to 10 x 20-inch composites resulted in several unanticipated results. One of the persistant problems that wasn't solved was wire gathering. This feature occurred on the last half of the sheet away from the line of explosive detonation. Without the wire being in alignment, the strengths would be poor. Associated with the gathering where the wires touched were places in which the entrapped jet had burned through the foils to give a pinhole or burnout spot which was detrimental to composite quality.

The wire gathering was severe when the 0.014 and 0.020-inch diameter was used. This wire required tension to keep it straight on the frames and any release of tension would allow spring-back. In this program it was not determined just what mechanism or combination of mechanisms allowed the wire to break loose from the end frames so the foils were moving at a faster rate than the wires to give the wire gathering defect.

Non-bond zones in the form of blisters were present. Reducing the amount of wire in the composite helped to reduce these non-bond zones but did not eliminate them. Non-bond in the larger composites was attributed to the foils not being flat which resulted in an inconsistent standoff distance between the foils.

Tearing and spallation cracks were present in small areas of the composites and were not in several cases related to edge effects. Rather, these cracks were related to high collapse angles, which were present when the standoff distance was too great. This again was attributed to the degree of flatness of the foils which did not allow a constant standoff distance.

The use of a harp or frame for holding the wire in place during explosive welding was very successful for small composites. Scaling up to large composites was not, and in part can be attributed to the problem of rolling absolutely flat refractory metal foils. Tearing and non-bond zones can be related to the quality of the foil. Another problem is impedance mismatch between foils and wires which was solved in the small scale experiments but could be a marginal situation in large composites.

Wire gathering, the most serious problem in the large scale composites, remains an unsolved phenomenon. Heavier wire does not demonstrate this phenomena. Based on the results of the program the problem is thought to be related to the tension in the smaller wires to keep them straight and the mechanics of accellerating the whole assembly without breaking the wires.

Although the ultimate goals were not achieved, the possibility of making large wire reinforced composites by explosive welding should not be discounted. Better quality control of materials to give flatter foils and straighter wires would be one of the first steps in achieving a good composite. A high speed photographic study of methods of accelerating the welding frame and foils would probably give the solutions to the problems associated with the wire gathering.

D

V. RECOMMENDATIONS

The success of making large wire reinforced composites by explosive welding will require a basic understanding of the acceleration modes that exist between the wire holding fixture and the actual area to be welded. It is recommended that in future work in this area, high speed photography and velocity probes be used to determine the conditions required for uniform acceleration. Redesign of the wire holding frame and buffer systems could then be based upon established facts rather than using an empirical approach to solve the problems.

Another aspect to be considered in future work is the quality control of the foils and wires. It is recommended that the fine wires be straightened and then wound on large diameter spools to keep permanent set to a minimum. In any wire specification ductility should be included so wire breakage during frame winding is not a problem. Higher crown rolls should be used during foil rolling to prevent an edge wrinkling due to more reduction in thickness at the edges than in the center of the foils as was the case in the present study.

APPENDIX I

Literature Survey

During the course of this program a continuing literature survey was conducted on composite structures; of interest were metal-metal filament systems and techniques of fabrication. Of particular interest were systems that had been explosively bonded as opposed to other fabrication procedures. The results of this survey are presented below.

The first reference in the open literature concerning explosively bonded metal-metal filament composites was the work of Jarvis and Slate[1]. These investigators bonded copper-tungsten filament composites using 13 layers of 0.012-inch copper foil and 0.006-inch diameter tungsten wire at a loading of 17 volume percent tungsten. Layup of the composite was done in a slotted anvil in which the sides of the foil were in contact with the sides of the slot. A buffer system comprising a metal compressor plate overlaid with PVC polymer and sheet explosive was used. The detonation velocity of the explosive was 7200 m/sec. Strengths of the composites were those predicted by the law of mixtures. One of the main disadvantages of this system was the slotted anvil which was massive and would not lend itself to large composite plates. However, the slot did maintain the edges showing the advantage of having a momentum arrestor. Jarvis and Slate indicated that a higher volume percent loading of tungsten could be achieved by using thinner foils.

Reece[2] explosively bonded composites of 1100-0 aluminum and AM-335 stainless steel wire and 2014-T6 aluminum and modular filament sheets of 455 stainless steel. An aluminum buffer sheet 0.125 with its lower side coated with 0.008-inch adhesive paper was used immediately over the matrices. Nitroguanadine was used as the explosive (2400 to 3700 in/sec detonation velocity). Rather than using spall rails along the edges, the buffer sheet was three inches wider along the edges than the composite matrix sheets. The filaments were rolled into the matrix sheets for positioning.

Reece[3] extended the above work to the present system C129Y columbium alloy and TZM molybdenum wire. In the layup procedure, the filaments were taped across

the ends of the filament layer and laid on top of the matrix sheets. Both 0.10 and 0.20-inch diameter filaments were used. At a volume percent TZM 0.020-inch diameter wire loading of 14.7 percent the tensile strength of the composite was 127,000 psi, whereas the law of mixtures would predict a strength of 106,000 psi. With the 0.010-inch diameter wire and a volume percent loading of 11.0 percent the strength was 136,000 psi. Some problem was encountered with wire cracking of the 0.020-inch diameter TZM unless the wire was stress relief annealed.

Kowalick and Hay[4] of Frankford Arsenal made explosively bonded composites of tungsten wires and 2024 aluminum. Both 0.05 and 0.01-inch wire was used which was lathe wound on mandrels, with the lathe speed determining the wire spacing. Volume fractions of tungsten were on the order of 15 percent. In tests with 10 to 15 layers of wire the bonding was incomplete using nitroguanadine on the explosive. For the second series of tests the assemblies were removed from the mandrel and bonded using 3 g/in^2 of Detasheet. The bottom layer still was not satisfactorily bonded in these tests.

Wylie, Williams and Crossland[5] explosively bonded high strength steel wire and aluminum composites. Again the volume percent loading was on the order of 15 percent. Their layup procedure consisted of wrapping the wire around the matrix plates, which has the disadvantage of warping thinner plates. Both screen and unidirectional composites were made. Strengths generally were those predicted by the law of mixtures. Crossland did indicate that about 17 volume percent loading of wire appeared to be the practical limit for explosively bond composites.

Miller[7] and his associates at Battelle used a Dynapak operation to make composites. The filaments used were SiC and Al_2O_3 in various combinations with titanium, Ti6Al 4V, nickel and Fe-Ci-Al. Of interest to the present program was the layup techniques for making the forging preforms. In some cases, the fibres were lathe wound on a mandrel to the desired spacing. Four mandrels were wound at a time and then cut apart for the individual preforms. Foils were used between the filament layers in some instances and the interstices

between the filaments filled with powder metal of the same alloy as the foils. This assembly was canned in steel, heated and forged to effect compaction of the composite. Although volume percent loadings of 35 percent were obtained in some instances, the strengths were lower than predicted, which in some cases was attributed to metal-fiber interaction at the bonding temperature.

Petrasek et al.[8, 9] investigated the use of refractory metal filaments for reinforcing nickel-base alloys. The nickel-base alloy was slip cast around the filament array and then presintered followed by hot pressing. Although TZM molybdenum wire was one of the filament materials, it was not satisfactory in these studies since it reacted with the matrix. However, the studies did indicate that the size of wire was important. Finer diameter wires have a higher strength than larger diameter wire. However, the matrix reacts with the wire area for strengthening as a function of the wire diameter. Therefore in a stress rupture test an optimum diameter of wire is predicted that is balanced between the original strength and the stress-rupture life expectancy. In general, the tungsten-base filaments were the best for reinforcing nickel-base alloys. Volume percent loading of up to 50 percent were obtained in this study.

The Solar Division[10] of International Harvestor conducted a study on tungsten filament reinforced columbium alloys. Part of this program was concerned with the development of new oxidation resistant columbium alloys. One of the alloys Cb-42Ti-4Ci-4Al-1V had a tensile strength greater than C129Y and had relatively good resistance to oxidation. This resistance was a fail-safe feature since the main resistance to oxidation was a silicide coating. The fail-safe life of a composite W-3Re filament was over 100 hours at 2000°F. A composite with 24 volume percent W-3Re supported a 21,000 psi load for almost 700 hours in air at 2100°F. Under cyclic conditions, the coating cracks and allows oxidation to take place. Extended heat treatments of the composites induces radial cracks in the matrix around the filaments and porisity at the interface. Matrix cracking near the filaments is a diffusion-dependent feature in which tungsten diffuses into the matrix. As a result, the low temperature transverse strength and ductility are reduced.

Harvey Engineering[11] has developed a diffusion bonding process for steel wire reinforced aluminum composites. Although excellent strengths have been achieved, there is an intermetallic layer formed around the wire during bonding which reduces the strength of the composite as the time at temperature is increased. For layup, a rotating frame was used to properly space the wires after which the whole assembly was canned in steel for hot pressing.

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5. H. K. Wylie, J. D. Williams, and B. Crossland, "Explosive Fabrication of Fibre Reinforced Aluminum, Proc. 3rd Int'l. Conf. of the Center for High Energy Forming," pp. 2.2.1 - 2.2.26, Vail,Colorado, July 1971.
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9. D. W. Petrasek and R. A. Signorelli, "Preliminary Evaluation of Tungsten Alloy Fiber-Nickel-Base Alloy Composites for Tuibojet Engine Applications," NASA Technical Note, NASA TND-5575, February 1970.
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APPENDIX II

Analysis of Shock Wave Interactions During Explosive Bonding of Composites

Longitudinal stress waves striking a boundary between two dissimilar metals will be partioned into a transmitted component and a reflected component. The amount of the incident stress, σ_I, that is transmitted, σ_T, and that reflected, σ_R, is a function of the specific acoustic impedance, ρc, of the individual materials involved. The relationships are:

$$(1) \qquad \frac{\sigma R}{\sigma_I} \doteq \frac{(\rho_2 C_2 - \rho_1 C_1)}{(\rho_1 C_1 + \rho_2 C_2)}$$

$$(2) \qquad \frac{\sigma T}{\sigma_I} = \frac{2\rho_2 Cl_2}{(\rho_1 Cl_1 + \rho_2 Cl_2)}$$

where $\rho_2 C_2$ = specific acoustic impedance metal being impacted

$\rho_1 C_1$ = specific acoustic impedance impacting metal

If the specific acoustic impedance in two metals differ by a factor of 3:1 then welding is almost impossible, and large variations less than 3:1 make welding difficult.

The specific acoustic impedances for the brass-tungsten and C129Y-TZM molybdenum welding systems are:

Metal	ρc $g/am^2/sec$
Steel	39×10^5
Aluminum	13.8×10^5
Brass	29.8×10^6
Tungsten	77.2×10^5
Molybdenum	53.2×10^5
C129Y	40.3×10^5

The steel-aluminum comprises the buffer system that is used. In making the analysis, the wire is treated as a separate layer since the foil layer impacts the wire first before contacting the next foil layer. Also, the foil-foil con-

tact can be treated as similar materials in contact so the reflected component is zero and the full wave is transmitted.

Using the buffer system in conjunction with one foil layer overlying the first wire layer the reflected and transmitted components of the longitudinal stress waves were calculated. This calculation is presented in Table A2-1, for the brass-tungsten system and Table A2-2 for the C129Y-TZM molybdenum system. The original wave is compressive during weldings and is considered to be unity at the start of welding for total transmitted and reflected.

TABLE A2-1

Partioning of Longitudinal Stress Waves in Brass-Tungsten System

Interface	Ratio of Compressive Wave Transmitted	Ratio Reflected Wave		Compressive Wave Transmitted	Reflected Wave Transmitted	
		Compressive	Tensile		Compressive	Tensile
Steel-Al	0.53	--	0.48	0.53	--	0.48
Al-Brass	1.37	0.37	--	0.73	0.19	--
Brass-W	1.44	0.42	--	1.04	0.31	--
W-Brass	0.57	--	0.42	0.60	--	0.25
Brass-W	1.44	0.42	--	0.86	0.25	--

TABLE A2-2

Partioning of Longitudinal Stress Waves in C129Y-TZM Molybdenum System

Interface	Ratio of Compressive Wave Transmitted	Ratio Reflected Wave		Compressive Wave Transmitted	Reflected Wave Transmitted	
		Compressive	Tensile		Compressive	Tensile
Steel-Al	0.53	--	0.48	0.53	--	0.48
Al-C129Y	1.49	0.47	--	0.79	0.25	--
C129Y-Mo	1.13	0.14	--	0.89	0.11	--
Mo-C129Y	0.86	--	0.14	0.77	--	0.12
C129Y-Mo	1.13	0.14	--	0.87	0.11	--

The partioning as presented is for waves interacting in solid materials in contact with one another. What is important in the case of explosive welding is the partioning of the longitudinal waves behind the point of collosion with respect to what type of stress is developed across the weld that is already laid down. A joint has to support any reflected tensile wave component, while if the waves at the joined interface are in compression there is no problem. Figure A2-1 schematically shows the reaction during welding of the reflected wave behind the interface. Using the aluminum buffer in contact with the brass plate results in a tensile component being generated at the interface immediately behind the point of welding, due to impedance mismatching. Substituting a thin steel foil between the deformable aluminum and the brass results in the ideal or compressive stress generation at the interface behind the weld.

In the situation of the C129Y alloy with an aluminum buffer in contact with it a similar situation exists with a tensile component being generated behind the point of initial contact. Using a steel buffer drastically reduces the tensile component as is shown in Figure A2-2.

There are other tensile components in the systems, particularly at the wire-second foil layer. However, the reactions would be complex due to the geometry of the system. With the wire being round there would be reflections from free surfaces before welding is obtained as well as the reflected tensile component after welding. Since welding is obtained in subsequent layers there is a distinct possibility that dampening effects occur due to geometry. The lowering of the tensile component in the first layer due to a dummy plate is an aid to welding in this case.

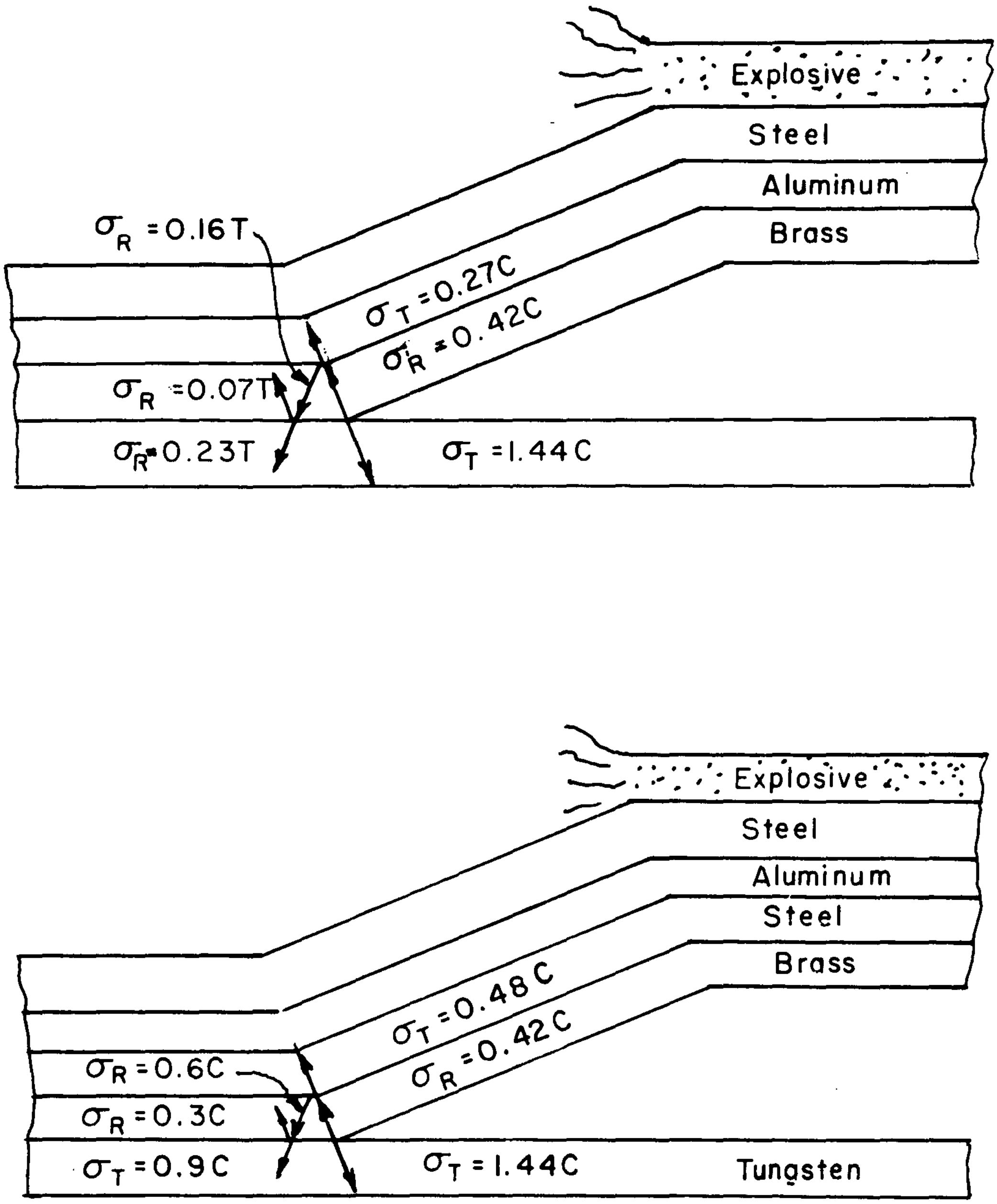
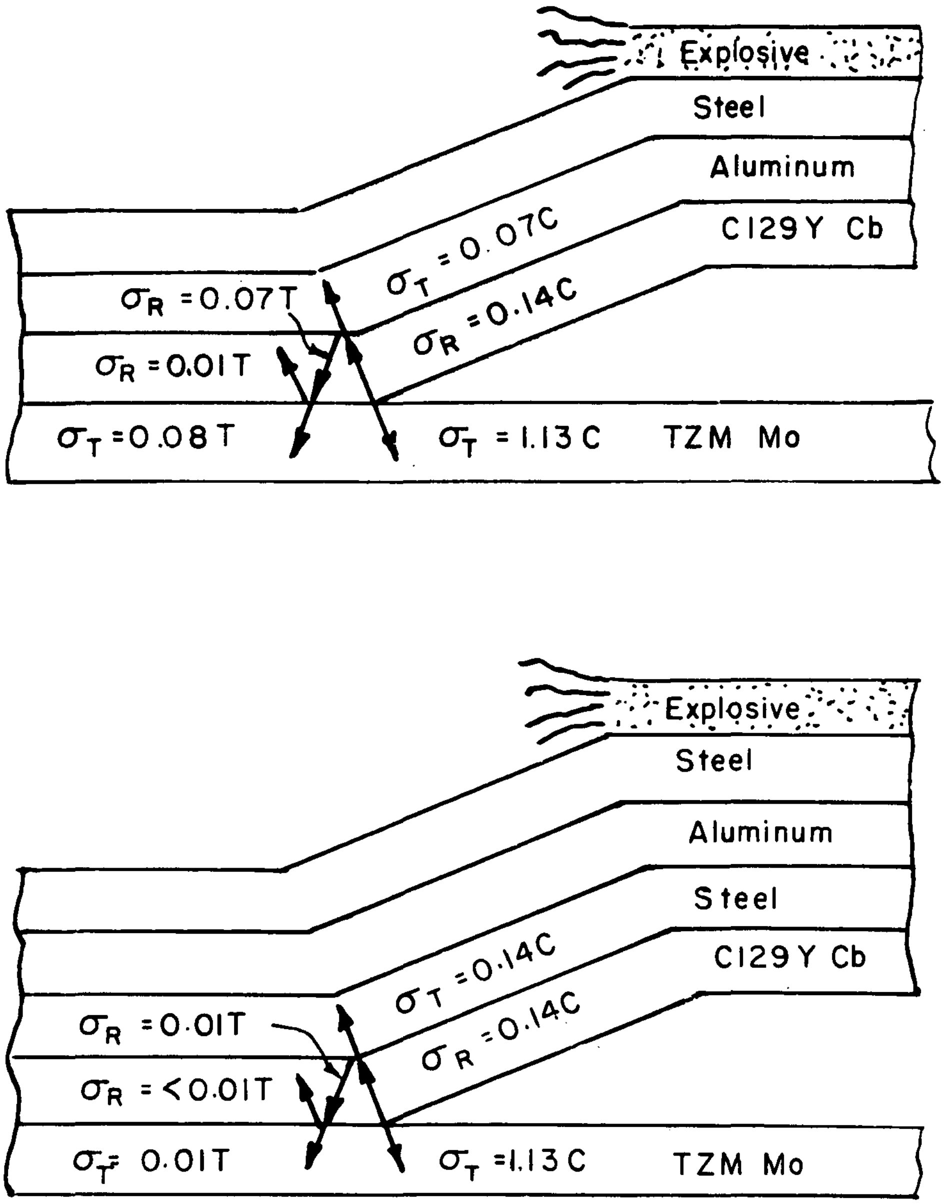

Explosive
Steel
Aluminum
Brass
σ_R = 0.16T
σ_T = 0.27C
σ_R = 0.42C
σ_R = 0.07T
σ_R = 0.23T
σ_T = 1.44C
Explosive
Steel
Aluminum
Steel
Brass
σ_T = 0.48C
σ_R = 0.42C
σ_R = 0.6C
σ_R = 0.3C
σ_T = 0.9C
σ_T = 1.44C
Tungsten

FIGURE A-1



Explosive
Steel
Aluminum
C129Y Cb
$\sigma_T = 0.07C$
$\sigma_R = 0.07T$
$\sigma_R = 0.14C$
$\sigma_R = 0.01T$
$\sigma_T = 0.08T$
$\sigma_T = 1.13C$
TZM Mo
Explosive
Steel
Aluminum
Steel
C129Y Cb
$\sigma_T = 0.14C$
$\sigma_R = 0.01T$
$\sigma_R = 0.14C$
$\sigma_R = <0.01T$
$\sigma_T = 0.01T$
$\sigma_T = 1.13C$
TZM Mo

FIGURE A-2